

Probing deviation of tribimaximal mixing and reach of θ_{13} using neutrino factory at CERN and ICAL detector at INO

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We investigate the deviation from tribimaximal mixing value and the reach of θ_{13} using neutrino factory at CERN and ICAL detector at INO.

High energy neutrino beams are now playing a very crucial role in determining the yet unknown features of neutrino physics. Determination of the neutrino mass hierarchy and determination of the mixing angle θ_{13} , probing CP violation effects at neutrino sector are the rich physics possibilities envisaged from the neutrino beam of a neutrino factory.

In the present work, we explore the possibility to observe the deviation, if any, of the neutrino mixing angles from their tribimaximal mixing [1] values using a long baseline neutrino experiment with the neutrino beam from muon storage ring at CERN and the detector at the India-based Neutrino observatory (INO) covering the distance of about 7152 Km. The tribimaximal mixing values for neutrino oscillations are given by $\sin \theta_{12} = 1/\sqrt{3} = \sin \theta_{\odot}$, $\sin \theta_{23} = 1/\sqrt{2} = \sin \theta_{\text{atm}}$ and $\theta_{13} = 0^\circ$ [2]. These results exactly follow from the theory with A_4 group symmetry [2]. It is also to be noted that the CERN-INO baseline length is close to the “magic baseline” length – the baseline length at which the CP effects on neutrino oscillation become virtually insignificant and hence reduce greatly the possibility of confusing matter effects on neutrino oscillation with the CP violation effects.

The detector at INO site is a magnetized Iron Calorimeter (ICAL) [3] which has the unique ability to determine the sign of the charge of the particle passing through it. Thus it has the capability to distinguish between the signature of $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation (appearance channel, μ^+ signal at ICAL) and the survival of ν_μ ($\nu_\mu \rightarrow \nu_\mu$ oscillation in disappearance channel; μ^- signal at ICAL) using the neutrino beam. The calculations done here are for the ICAL detector of is 50 kTon mass and with an exposure time of 5 years.

The reach of θ_{13} for ICAL at INO detector is also investigated. This is defined as the lowest value of θ_{13} that can be probed by ICAL for different energies of initial decaying muons at the horn of the neutrino factory.

Neutrino beams are generated from the decay of muons, $\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$ from the straight section of the muon storage ring [4, 5]. For unpolarized muon beam, the flux distributions of ν_μ and $\bar{\nu}_e$ are given by

$$\left(\frac{d^3 N}{dt dA dE_\nu} \right)_{lab}^{\nu_\mu} = \frac{4g_{lab}J^2}{\pi L^2 E_\mu^3} E_{\nu_\mu}^2 \left(3 - 4 \frac{E_{\nu_\mu}}{E_\mu} \right) \quad (1)$$

$$\left(\frac{d^3 N}{dt dA dE_\nu} \right)_{lab}^{\bar{\nu}_e} = \frac{28g_{lab}J^2}{\pi L^2 E_\mu^4} E_{\bar{\nu}_e}^2 (E_\mu - 2E_{\bar{\nu}_e}) \quad (2)$$

where g_{lab} is the number of muons produced, J is the Jacobian factor arising due to transformation from rest frame to lab frame and is given by

$$J = \frac{1}{\gamma(1 - \beta \cos \theta)} \quad (3)$$

E_μ is the energy of the decaying muon and E_{ν_μ} and $E_{\bar{\nu}_e}$ are energies of the neutrinos produced due to decay of these muons. Also, γ is the boost factor and $\beta = p_\mu/E_\mu$. The angle θ is the off axis angle which we set to zero.

For our analysis, we set the parameters as $g_{lab} = 0.35 \times 10^{20}$ considering 35% efficiency of the produced muon number. The parameter L is the length traversed by the neutrino from the source to the detector through the earth. In the present work, as mentioned, we take $L = 7152$ Km which is the distance between the source at CERN to the detector at the INO site at PUSHEP (11°5'N, 76°6'E) [6]. The distribution of flux for both $\bar{\nu}_e$ and ν_μ are shown in Fig. 1 and Fig. 2 respectively, where $E_{\bar{\nu}_e}$ varies from 0-10 GeV and E_{ν_μ} varies from 0-15 GeV and we observe for both the cases a large number of muons hitting the detector.

We consider here a three flavour neutrino oscillation with matter effects [7] due to the passage of the neutrino through the earth. It may be noted here that the average earth matter density for CERN-INO baseline can be calculated to be 4.15 gm/cm³.

We consider the $\nu_\mu \rightarrow \nu_\mu$ as well as $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ mode in the three flavour oscillation scenario. The interaction of ν with the ICAL (Iron Calorimeter) detector proposed at INO site are mainly arising through quasi-elastic (QE) and Deep inelastic scattering (DIS). At low energy we have considered QE mode ($E_\nu \leq 1$ GeV), and for $E_\nu > 1$ GeV the dominant contribution will come from DIS.

We emphasise here that the resolution function of the detector obtained from the exact simulation of the ICAL detector using GEANT 3.2 simulation code has been included.

We have calculated the total muon yields for CERN-INO baseline for the deviation from tribimaximal mixing and the maximum and the minimum muon yield values for such deviation are tabulated in Table 1. In order to estimate the deviation, we take the experimentally obtained range for the three mixing angles given as $30^\circ \leq \theta_{12} \leq 38^\circ$, $38^\circ \leq \theta_{23} \leq 53^\circ$ and $\theta_{13} < 12^\circ$. The calculation is repeated for several values of the CP violation phases, δ .

The wrong sign muon yield for the best fit values of the oscillation parameters [7] is also calculated for the CERN-INO distance. This is tabulated in Table 2.

CERN-INO	δ CP	θ_{13}	Muon yield		Boost
			Max	Min	
50 kton 5 years	0°	9°	605835	486304	472.0 $E_\mu=50$ GeV
	0°	6°	613035	483768	
	270°	6°	626210	491390	

Table 1. Variations of muon yield at INO with the deviation from tribimaximal mixing for neutrino beam from a neutrino factory at CERN

CERN-INO	E_μ (GeV)	Muon Yield		δ CP	θ_{13} (in degrees)
		Wrong sign μ	Right sign μ		
50 kton 5 years	50	79447	458893	0°	6
		85834	449788	0°	9
		72827	477637	90°	6
		75857	473150	90°	9

Table 2. The wrong sign muon yield at INO for a neutrino beam from CERN.

The reach of θ_{13} at the ICAL detector at INO is also addressed. For this purpose, we first calculate the wrong sign muon yield for $\theta_{13} = 0.0$. Then we investigate the minimum value of θ_{13} that will be required to obtain the wrong sign muon yield with 1σ deviation. In this case we consider the statistical error only. The process is repeated for the inverted mas hierarchy as well.

In Fig. 3, the $\sin^2 2\theta_{13}$ reach, thus calculated, is shown for different values of muon energies (i.e. for different values of the boost) that are allowed to decay in a neutrino factory. Here too the CERN-INO baseline is considered. There is no significant

difference for the θ_{13} reach values for normal and inverted mass hierarchies. It is also seen from Fig. 3 that INO is capable of detecting θ_{13} as low as $\sim 1^\circ$ for $E_\mu \sim 25$ GeV. The reach is further reduced to $\sim 0.2^\circ$ for higher boost (higher $E_\mu \sim 60$ GeV). This is an encouraging result.

A detailed Geant-based study is under progress.

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Figure Captions

Fig. 1 The $\bar{\nu}_e$ flux from a neutrino factory with muon energy $E_\mu = 50$ GeV. See text for details.

Fig. 2 The ν_μ flux from a neutrino factory with muon energy $E_\mu = 50$ GeV. See text for details.

Fig. 3 The reach of $\sin^2 2\theta_{13}$ at INO for neutrinos from a neutrino factory at CERN for various energies E_μ of decaying muons. See text for details.

